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**DISPLAY SYSTEM INCORPORATING TRILINEAR  
ELECTROMECHANICAL GRATING DEVICE**

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# **DISPLAY SYSTEM INCORPORATING TRILINEAR ELECTROMECHANICAL GRATING DEVICE**

## **FIELD OF THE INVENTION**

5                    This invention relates to a display system with a linear array of electromechanical grating devices that is scanned in order to generate a two-dimensional image. More particularly, the invention relates to a display system containing a trilinear array of electromechanical grating devices.

## **10                    BACKGROUND OF THE INVENTION**

                  Spatial light modulators based on electromechanical grating devices are important for a wide range of applications, including display, data storage, spectroscopy and printing. Such systems require large numbers of individually addressable devices in either a linear or area array, with over a  
15   million addressable devices desirable for an area modulator array in a high-quality display.

                  Linear arrays are particularly advantaged over their area array counterparts by virtue of higher resolution, reduced cost, and simplified illumination optics. Of particular interest: linear arrays are more suitable  
20   modulators for laser light than are their two-dimensional counterparts. Grating Light Valve (GLV) linear arrays, as described in U.S. Patent No. 5,311,360 (Bloom et al.) are one earlier type of linear array that offers a workable solution for high-brightness imaging using laser sources, for example. Another experimental type of linear array just recently disclosed and in early development  
25   stages is the flexible micromirror linear array, as described in the article "Flexible micromirror linear array for high resolution projection display" by Francis Picard, et al. in *MOEMS Display and Imaging Systems, Proceedings of SPIE* Vol. 4985 (2003). The prototype flexible micromirror linear array described in the Picard et al. article employs a line of reflective "microbridges" which are individually  
30   switched to modulate light to form a linear image.

                  Recently, an electromechanical conformal grating device consisting of ribbon elements suspended above a substrate by a periodic sequence

of intermediate supports was disclosed by Kowarz in U.S. Patent No. 6,307,663, issued on October 23, 2001, entitled "SPATIAL LIGHT MODULATOR WITH CONFORMAL GRATING DEVICE." The electromechanical conformal grating device is operated by electrostatic actuation, which causes the ribbon elements to conform around the support substructure, thereby producing a grating. The device of '663 has more recently become known as the conformal GEMS device or, more simply, GEMS device, with GEMS standing for grating electromechanical system. The GEMS device possesses a number of attractive features. It provides high-speed digital light modulation with high contrast and good efficiency. In addition, in a linear array of GEMS devices, the active region is relatively large and the grating period is oriented perpendicular to the array direction. This orientation of the grating period causes diffracted light beams to separate in close proximity to the linear array and to remain spatially separated throughout most of an optical system and enables a simpler optical system design with smaller optical elements.

Display systems based on a linear array of GEMS devices were described by Kowarz et al. in U.S. Patent 6,411,425, entitled "ELECTROMECHANICAL GRATING DISPLAY SYSTEM WITH SPATIALLY SEPARATED LIGHT BEAMS," issued June 25, 2002 and by Kowarz et al. in U.S. Patent 6,476,848, entitled "ELECTROMECHANICAL GRATING DISPLAY SYSTEM WITH SEGMENTED WAVEPLATE," issued Nov. 5, 2002. Display systems based on GLV devices are disclosed in U.S. Patent No. 5,982,553, entitled "DISPLAY DEVICE INCORPORATING ONE-DIMENSIONAL GRATING LIGHT-VALVE ARRAY" issued to Bloom et al. on November 9, 1999.

Current GLV and GEMS color display system architectures employ three separate color paths, Red, Green, and Blue (RGB), each color path provided with a linear array of electromechanical grating devices. Each linear array of electromechanical grating devices modulates its component red, green, or blue laser light. The resulting modulated light beams are then combined onto the same output axis to provide a full-color image that is then scanned to the display

screen. Referring to Fig. 1, there is shown a prior art display system 10 using three separate optical paths in this way.

For red color modulation, a red light source 70r, typically a laser, provides illumination that is conditioned through a spherical lens 72r and a cylindrical lens 74r and directed towards a turning mirror 82r. Light reflected from turning mirror 82r is modulated by diffraction at an electromechanical grating light modulator 85r. Modulated diffracted light from electromechanical grating light modulator 85r is diffracted past turning mirror 82r and to a color combiner 100, such as an X-cube or other dichroic combiner. The modulated light from color combiner 100 is then directed by a lens 75, through an optional cross-order filter 110 (not shown), to a scanning mirror 77 for projection onto a display surface 90. Green color modulation uses a similar set of components for providing light to color combiner 100, with a green light source 70g, typically a laser, providing illumination through a spherical lens 72g and a cylindrical lens 74g and directed towards a turning mirror 82g. Light reflected from turning mirror 82g is modulated by diffraction at an electromechanical grating light modulator 85g. Modulated diffracted light from electromechanical grating light modulator 85g is diffracted past turning mirror 82g and to color combiner 100. Similarly, blue light source 70b, typically a laser, provides illumination through a spherical lens 72b and a cylindrical lens 74b and directs light towards a turning mirror 82b. Light reflected from turning mirror 82b is modulated by diffraction at an electromechanical grating light modulator 85b, diffracted past turning mirror 82b and to color combiner 100.

In order to maintain precise color registration with the system of Fig. 1, each of the three linear arrays, electromechanical grating light modulators 85r, 85g, and 85b, must be aligned to each other, to within sub-pixel tolerances. This precision of alignment is difficult to obtain. Moreover, this alignment must prove stable so that it can be maintained over a range of temperatures and other environmental conditions, such as shock and vibration. Color combiner 100 is a particularly costly component and can be the source of undesirable image aberrations.

One design solution that eliminates the color channel alignment problem is color-sequential operation, whereby a single electromechanical grating light modulator serves to modulate each color light in sequence. This type of system is described, for example, in the disclosure of U.S. Patent No. 6,411,425  
5 entitled "Electromechanical Grating Display System with Spatially Separated Light Beams" to Kowarz et al. (see cols. 9-10). However, as noted in the '425 Kowarz et al. disclosure, color-sequential techniques, by modulating only one color at a time, effectively waste two-thirds of the available light. Thus, although color-sequential solutions minimize alignment concerns, these solutions have  
10 performance drawbacks.

Thus, it can be seen that there would be advantages to a projection solution that provides the performance benefits of electromechanical grating light modulators without requiring frequent adjustment of alignment for each color path or requiring complex and costly mounting apparatus that would be able to  
15 maintain alignment over a wide range of operating conditions, and that provides a compact, low-cost apparatus, without the requirement for a color-combining prism.

#### SUMMARY OF THE INVENTION

20 The present invention is directed to overcoming one or more of the problems set forth above. Briefly summarized, according to one aspect, the present invention provides a display system, comprising:

- a) a light modulator having at least three linear arrays of light modulating devices on a common substrate;
- 25 b) at least one light source producing at least three colors of light for illuminating the at least three linear arrays;
- c) a lens for creating line images of the at least three linear arrays on a screen; and
- d) a scanning mirror for sweeping the line images to create a two-  
30 dimensional image.

It is a feature of the present invention that it uses arrays of electromechanical grating devices that are fabricated on a common substrate.

It is an advantage of the present invention that it provides a full-color display system using arrays of electromechanical grating devices that does  
5 not require alignment of individual color paths for modulated light.

It is an advantage of the present invention that it provides a full-color display system using arrays of electromechanical grating devices with a reduced number of components, allowing design of a more compact and lower cost apparatus than provided by earlier designs. With its reduced number of  
10 components and minimized requirements for adjustment, the apparatus of the present invention provides a robust solution for imaging using electromechanical grating array devices.

It is a further advantage of the present invention that it eliminates the need for a color combining cube in the path of modulated light.

15 These and other objects, features, and advantages of the present invention will become apparent to those skilled in the art upon a reading of the following detailed description when taken in conjunction with the drawings wherein there is shown and described an illustrative embodiment of the invention.

## 20 BRIEF DESCRIPTION OF THE DRAWINGS

While the specification concludes with claims particularly pointing out and distinctly claiming the subject matter of the present invention, it is believed that the invention will be better understood from the following description when taken in conjunction with the accompanying drawings, wherein:

25 Fig. 1 is a schematic block diagram showing a prior art display apparatus employing an electromechanical grating light modulator in each of three color modulation channels;

Fig. 2 is a schematic block diagram showing the arrangement of color modulation components in one embodiment of the present invention;

30 Fig. 3 is a plan view showing three arrays of electromechanical grating light modulators on a single substrate according to one embodiment;

Fig. 4a is plan view showing routing of control traces for three arrays of electromechanical grating light modulators according to another embodiment;

5 Fig. 4b is a side view showing the arrangement of a control trace used in the embodiment of Fig. 4a;

Fig. 5 is a plan view showing a scheme for routing of control traces from driver circuits for three arrays of electromechanical grating light modulators according to another embodiment;

10 Fig. 6 is a schematic block diagram showing an arrangement of color modulation components in an alternate embodiment of the present invention;

Fig. 7 is a schematic block diagram showing an arrangement of color modulation components in another alternate embodiment of the present invention, employing a cover prism as an alternative to a cover plate; and,

15 Fig. 8 is a plan view of a patterned micromirror used in some embodiments of the present invention.

To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures.

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## DETAILED DESCRIPTION OF THE INVENTION

The present description is directed in particular to elements forming part of, or cooperating more directly with, apparatus in accordance with the invention. It is to be understood that elements not specifically shown or  
25 described may take various forms well known to those skilled in the art.

For the description that follows, components specific to a single color path may be more particularly identified with a letter appended to the part number. Where used, letters correspond to color paths; for example, "r" is appended for red, "b" for blue, "g" for green.

30 Referring to Fig. 2, there is shown an embodiment of display system 10 of the present invention, employing a trilinear array of light modulating devices 60 for modulating light from red, green, and blue light sources 70r, 70g,

and 70b. A dichroic combiner 94 is provided in the illumination path, for directing illumination from each of red, green, and blue light sources 70r, 70g, and 70b toward a patterned micromirror assembly 62. Patterned micromirror assembly 62, in turn, directs the illumination for each color to a corresponding

5 linear array of light modulating devices 185r, 185g, or 185b in trilinear array of light modulating devices 60. Referring to Fig. 8, there is shown an arrangement of patterned micromirror assembly 62 for one embodiment. An arrangement of reflective segments 24 is provided, with transmissive regions 26 spaced between reflective segments 24. Reflective segments 24 may be fabricated using

10 deposition of reflective metallic materials such as aluminum or silver, applied using shadow mask techniques or other suitable fabrication techniques. Transmissive regions 26 may be fabricated in a number of ways, such as applying an anti-reflective coating onto a glass substrate, for example.

In a preferred embodiment, trilinear array of light modulating

15 devices 60 is formed from three separate electromechanical grating light modulator sections, aligned on the same substrate, each electromechanical grating light modulator section corresponding to a linear array of light modulating devices 185r, 185g, or 185b. In one embodiment, linear array of light modulating devices 185r, 185g, and 185b are GEMS devices. Alternately, any one or all of

20 linear array of light modulating devices 185r, 185g, or 185b could be a GLV device or a flexible micromirror linear array, as described in the Picard et al. article noted in the background section hereinabove. As is well-known to those skilled in the art, the specific layout and design of supporting optical elements in display system 10 must be tailored to the specific type of light modulating device

25 that is used.

Referring again to Fig. 2, reflective segments 24 of patterned micromirror assembly 62 are angularly aligned with each linear array of light modulating devices 185r, 185g, and 185b in display system 10. Modulated light passes through the glass substrate of patterned micromirror assembly 62 and is

30 then directed through lens 75 and optional cross-order filter 110, placed at focal distance  $f$  from lens 75, to scanning mirror 77 for forming the final color image on display surface 90, as was described with reference to the prior art apparatus of



Fig. 1. It is worthwhile to observe that dichroic combiner 94 can be an X-cube or X-prism or similar device. However, in contrast to the arrangement of Fig. 1, this component is in the illumination path, rather than in the path of modulated light.

Thus, there is wider tolerance for fabrication of dichroic combiner 94 of Fig. 2

5 than for the conventional X-prism used as color combiner 100 in Fig. 1, allowing this component to have significantly lower cost. For example, an X-prism used as color combiner 100 would be smaller than an X-prism used for modulated light. Additional cost benefits relate to the overall optical performance requirements for projection optics. With the arrangement of Fig. 1, for example, lens 75 requires a  
10 longer back focal length and must provide acceptable imaging through color combiner 100, since color combiner 100 is in the object path of lens 75. Moving the color-combining function to the illumination path thus simplifies lens 75 design and cost.

Other types of combining components could alternately be used in  
15 the illumination path; typically, these components employ an arrangement of dichroic surfaces. While some amount of alignment is needed for red, green, and blue light sources 70r, 70g, and 70b, the arrangement of Fig. 2 allows some tolerance for imperfect alignment.

It is instructive to observe that the three linear array of light  
20 modulating devices 185r, 185g, or 185b provide line images that are spatially separated. This necessitates incorporating a time delay of some duration into the display data stream, so that lines of the output image are written at the appropriate time, as paced by scanning hardware and depending on spacing between the three linear array of light modulating devices 185r, 185g, or 185b. At any one moment,  
25 for example, linear array of light modulating devices 185r may be writing a line (*line n*) of the output image; linear array of light modulating devices 185g may be writing an adjacent or nearby line (*line (n + 1) or line (n + 2)*) of the output image; and linear array of light modulating devices 185b may be writing a further line of the output image. It may not be feasible or desirable to write adjacent lines  
30 of different colors at precisely the same time; instead, some amount of timing delay would be required. In any case, some amount of timing offset is needed in

order to compensate for spacing between the three linear array of light modulating devices 185r, 185g, or 185b.

Referring now to Fig. 3, there is shown a plan view representation of linear arrays of light modulating devices 185r, 185g, and 185b on trilinear  
5 array of light modulating devices 60 in a simple embodiment. In operation, each linear array of light modulating devices 185r, 185g, and 185b operates independently, having its own control signals, routed from driver circuitry (not shown in Fig. 2).

#### 10 Options for Control Signal Routing

In the embodiment of Fig. 3, there are difficulties in properly routing control signals to green linear array of light modulating devices 185g, shown in the center, due to its position between red and blue linear arrays of light modulating devices 185r and 185b, respectively. Fig. 4a shows an arrangement of  
15 control traces 64 and contacts 66 that could be used to provide this electrical connection in one embodiment. In the embodiments of Figs. 4a and 4b, linear arrays of light modulating devices 185r, 185g, and 185b are depicted as GEMS devices. Each set of ribbon elements 46 has a corresponding contact 66 used for activation. Interspersed with ribbon elements 46 in the outer red and blue linear  
20 array of light modulating devices 185r and 185b are control traces 64 that provide pass-through control signals for green linear array of light modulating devices 185g. Ribbon elements 46 are provided with underlying supports 29, as was described in U.S. Patent No. 6,307,663, cited earlier. Control traces 64 are provided with additional retainers 30, as shown in Fig. 4a and in the side view of  
25 Fig. 4b, so that these structures do not bend and thereby unintentionally act as an active part of the optical grating for outer red and blue linear array of light modulating devices 185r and 185b. This arrangement, using both retainers 30 and supports 29 for control traces, helps to minimize cross-talk between color channels.

30 The arrangement of Figs. 4a and 4b is workable in particular because the relative resolution of red, green, and blue modulated light need not be the same. As is well known in the imaging arts, it is most important for the green

modulated light to have high resolution. Lower resolution of the other colors, particularly of blue, is acceptable and has little impact on image quality. In Fig. 4a, for example, the resolution of green linear array of light modulating devices 185g is higher than that of red or blue linear array of light modulating devices 185r or 185b.

Using a lower resolution value for blue, the arrangement shown in Fig. 5 rearranges the relative positions of linear array of light modulating devices 185r, 185g, and 185b from that of Fig. 4a. In Fig. 5, blue linear array of light modulating devices 185b has lower resolution and is positioned between red and green linear array of light modulating devices 185r and 185g. Red, green, and blue driver chips 68r, 68g, and 68b can then route signal lines using control traces 64 for providing electrical connection in a simple pattern as shown. Because blue linear array of light modulating devices 185b has lower resolution, fewer control traces 64 are needed for this middle section of trilinear array of light modulating devices 60.

In a preferred embodiment for use with an HDTV system having 1080 x 1920 resolution, the following dimensions are illustrative:  
540 blue pixels (half the number of green pixels and of red pixels)  
3 um per line/ 1 um spacing for control traces 64  
135 x 4 um = 540 um space requirement for control traces 64 to blue pixels, plus additional margin.

#### Alternate Embodiments for Display System 10

Referring to Fig. 6, there is shown an alternate embodiment for display system 10 using a combination with a dichroic combiner 92, an achromatic polarizing beamsplitter 93, an achromatic quarter waveplate 96, and a patterned stop assembly 52, having a stop 54 for each modulated light path (rather than having reflective segments 24 as does patterned micromirror assembly 62). Here, dichroic combiner 92 provides a single surface for reflecting red and green light and transmitting blue light towards polarizing beamsplitter 93. Achromatic quarter waveplate 96 could alternately be a multiorder quarter wave plate. The embodiment of Fig. 6 effectively de-couples the input path (illumination) from the

output path (modulated light), making the arrangement of Fig. 6 advantageous over the arrangement of Fig. 2, and easing tolerance requirements. However, both polarization beamsplitter 93 and achromatic quarter waveplate 96 are more costly with this arrangement.

5                   Referring to Fig. 7, there is shown another alternate embodiment having advantages similar to the embodiment of Fig. 6 and eliminating the need for both polarization beamsplitter 93 and achromatic quarter waveplate 96, relatively expensive components. Here, illumination is incident to trilinear array of light modulating devices 60 at an oblique angle. A cover prism 98, with the  
10 arrangement of surfaces as shown in Fig. 7, serves to eliminate the requirement for a separate cover glass near the surface of trilinear array of light modulating devices 60; alternately, cover prism 98 could simply be bonded to the cover glass. The cover prism 98 arrangement thereby removes the cause of undesirable cover reflection that would otherwise contribute to reduced contrast with light oblique  
15 to the surface of trilinear array of light modulating devices 60. As shown in Fig. 7, light enters and exits from trilinear array of light modulating devices 60 at close to normal angles with respect to surfaces of cover prism 98.

                  The invention has been described with reference to a preferred  
20 embodiment. However, it will be appreciated that variations and modifications can be effected by a person of ordinary skill in the art without departing from the scope of the invention. Thus, what is provided is a display apparatus and method using a trilinear electromechanical grating light modulator to provide high-quality imaging at lower cost.

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**PARTS LIST**

10	Display system
24	Reflective segment
26	Transmissive region
29	Support
30	Retainer
46	Ribbon elements
48	Retaining elements
52	Patterned stop assembly
54	Stop
60	Trilinear array of light modulating devices
62	Patterned micromirror assembly
64	Control trace
66	Contact
68, 68r, 68g, 68b	Driver chip; Driver chip, red; Driver chip, green; Driver chip, blue.
70, 70r, 70g, 70b	Light source; Light source, red; Light source, green; Light source, blue.
72, 72r, 72g, 72b	Spherical lens; Spherical lens, red; Spherical lens, green; Spherical lens, blue
74, 74r, 74g, 74b	Cylindrical lens; Cylindrical lens, red; Cylindrical lens, green; Cylindrical lens, blue
75	Lens
77	Scanning mirror
82, 82r, 82g, 82b	Turning mirror; Turning mirror, red; Turning mirror, green; Turning mirror, blue
85	Electromechanical grating light modulator
85r, 85g, 85b	Electromechanical grating light modulator, red; Electromechanical grating light modulator, green; Electromechanical grating light modulator, blue
90	Display surface
92	Dichroic combiner
94	Dichroic combiner

93 Polarizing beamsplitter

96 Quarter-wave plate

98 Cover prism

100 Color combiner

110 Cross-order filter

185r, 185g, 185b Linear array of light modulating devices, red; Linear array  
of light modulating devices, green; Linear array of light modulating devices, blue